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# **Final Technical Report**

NON-EVAPORATIVE COOLING USING SPIN-EXCHANGE  
COLLISION IN AN OPTICAL TRAP

FA9550-06-1-0190

**Submitted by**  
**Jacob L. Roberts**  
**Colorado State University**

**20090429213**

## Abstract

This report describes, with references, three areas of research that addressed open questions relevant to the implementation of a novel non-evaporative cooling technique for ultracold gases, called collision-assisted Zeeman (CAZ) cooling. First, robust CAZ cooling requires efficient optical pumping in dense ultracold gases in which reabsorption of scattered photons is a serious limitation. Mitigation of reabsorption in such gases via the temporal and spatial modulation of light is reported. Second, the implementation of CAZ cooling requires that a sufficient number of  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  atoms be simultaneously trapped in an optical trap. The loading of  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  both singly and simultaneously in an optical trap from a Magneto-optical trap has been achieved and was optimized and characterized. Third, light-assisted collision rates in an  $^{85}\text{Rb}/^{87}\text{Rb}$  mixture were measured in detail. These measurements were crucial to a full understanding of the relevant physics in simultaneously loading these two isotopes into an optical trap. As a result of all of this work, design criteria for collision-assisted Zeeman cooling have been met and exceeded.

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### **List of publications resulting from this project**

1. Anthony R. Gorges, Ansel J. Foxley, David M. French, Christopher M. Ryan, and Jacob L. Roberts, "Suppression of reabsorption in ultracold gases via modulation of light," Phys. Rev. A 75, 053403 (2007).
2. Anthony R. Gorges, Nicholas S. Bingham, Michael K. DeAngelo, Mathew S. Hamilton, and Jacob L. Roberts, "Light-assisted collisional loss in a 85/87Rb ultracold optical trap," Phys. Rev. A 78, 033420 (2008).
3. Mathew S. Hamilton, Anthony R. Gorges, and Jacob L. Roberts, "Influence of optical molasses in loading a shallow optical trap," Phys. Rev. A 79, 013418 (2009).

### **Students supported during the grant period**

David French (B.S, December 2006)

Ansel Foxley (Masters, May 2006)

Anthony Gorges (Ph. D., anticipated graduation August 2009)

Mathew Hamilton (Ph. D., anticipated graduation December 2010)

### **Theses generated from work performed during the grant period**

*Anticipated*, Anthony R. Gorges, "Ultracold Optical Trapping Physics in a Heteronuclear  $^{85}\text{Rb}/^{87}\text{Rb}$  mixture", Colorado State University Thesis, 2009. (*Title may be subject to change, but the author, year, and institution should be correct*).

### **Conference presentations and invited talks during the grant period**

#### **Invited**

1. 2007 "Of Escaping Photons and Twinkling Atoms: Mitigating Reabsorption in Ultracold Gases via Modulation of Light." Colorado State University, Physical Chemistry Seminar, Fort Collins, CO.



2. 2007 “Of Escaping Photons and Twinkling Atoms: Mitigating Reabsorption in Ultracold Gases via Modulation of Light.” Kansas State University Atomic Physics Seminar, Manhattan, KS.
3. 2007 “Of Escaping Photons and Twinkling Atoms: Mitigating Reabsorption in Ultracold Gases via Modulation of Light.” Optical Science and Engineering Program Seminar, University of Colorado, Boulder, CO.

### **Contributed**

1. 2008 “Light-assisted collisional losses in an 85/87Rb Optical Trap,” talk, 39th Annual Meeting of the Division of Atomic, Molecular, and Optical Physics (DAMOP) of the American Physical Society, State College, PA.
2. 2007 “Simultaneous loading of 85Rb and 87Rb into an Optical Trap from a MOT”, poster, 38th Annual Meeting of the Division of Atomic, Molecular, and Optical Physics (DAMOP) of the American Physical Society, Calgary, AB, Canada
3. 2006 “Reabsorption mitigation using frequency-broadened light”, talk, 37th Annual Meeting of the Division of Atomic, Molecular, and Optical Physics (DAMOP) of the American Physical Society, Knoxville, TN
4. 2006 “Sub-Doppler calibration of a DAVLL signal using a compact design”, talk, 37th Annual Meeting of the Division of Atomic, Molecular, and Optical Physics (DAMOP) of the American Physical Society, Knoxville, TN

## Overview of Objectives

The research program that was supported by this grant has as its goal the implementation and evaluation of a novel cooling scheme for ultracold gases, called collision-assisted Zeeman cooling (CAZ) [1]. This cooling scheme relies on a combination of inelastic spin-exchange collisions and optical pumping in order to cool an ultracold gas of atoms from temperatures typical of those achieved in standard laser cooling down to temperatures near quantum phase transitions, such as Bose-Einstein condensation. Unlike evaporative cooling, this technique does not require the loss of atoms in order to cool. While CAZ cooling should work for a variety of different atomic species, in this project a combination of  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  is used.

In order for this cooling to be successful, there are numerous requirements that have to be fulfilled. In particular, a sufficient number of both  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  atoms have to be simultaneously loaded into an optical trap. Also, the optical pumping that is part of the cooling needs to be performed without a significant amount of induced heating and loss. The research that has been performed over the time period of this grant has focused on the study and achievement of these requirements. Before the research conducted here, the simultaneous loading of  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  into an optical trap from a Magneto-optic trap (MOT) had not been reported. The efficiency of this dual loading process was thus an open question, and formed one of the major areas of investigation during the time period of this grant. As part of the evaluation and optimization of optical trap loading efficiency, light-assisted collisions were studied in this heteronuclear, optically trapped gas. The knowledge gained from these light-assisted collision studies has helped us optimize the optical trap loading process, helped us understand some of the sensitivities and variations in the performance of our experimental apparatus, and will be useful in mitigating losses due to light-assisted collisions during optical pumping in CAZ cooling.

In addition to these efforts related to the efficient loading of  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  into an optical trap in sufficient numbers for CAZ cooling, the problem of reabsorption in dense ultracold gases was also studied. In order for any optical pumping to be successful, the atoms being pumped must scatter the pumping light out of the gas. Reabsorption interferes with this process as the scattered light is absorbed in the gas rather than escaping. This reabsorption of scattered light has been a major limitation to the performance of laser-cooling-based non-evaporative cooling experiments conducted in the past. We have conducted experiments showing that it is possible

to reduce the amount of reabsorption that occurs in an optically dense sample by modulating the optical pumping light in both frequency and space. Our results can be understood theoretically, and we predict that our method can be extended to achieve a substantial reduction in reabsorption during CAZ cooling.

## **Summary of Accomplishments during the Grant Period**

There are three areas of accomplishment that were achieved during this grant period. The results we have obtained in each of these areas have resulted in a peer-reviewed publication. In roughly chronological order these accomplishments are:

### **I. Mitigation of reabsorption in an optically dense ultracold gas via light modulation.**

By studying the amount of heat induced by light pulses in an optically dense ultracold gas, we found that we could reduce the amount of heat due to reabsorption by modulating the light pulse in both frequency and space. Our measurements showed that we could reduce the amount of reabsorption-induced heat by a factor of 2. We were able to explain our observations in terms of a calculation using optical Bloch equations that included the presence of the spontaneously scattered light in the gas. In light of these calculations, we expect that the amount of reduction in reabsorption-induced heating can be reduced beyond a factor of 2, to a factor of 4 or more in our present experimental set-up.

We expect this mitigation technique to have a direct impact on the cooling efficiency that we can achieve in CAZ cooling. Based on other research groups' experience with cooling involving optical pumping [2], the ultimate performance of CAZ cooling is likely to be limited by the amount of reabsorption-induced heating that is produced during optical pumping. A reduction of a factor of 2 in the reabsorption-induced heat should result in roughly a factor of 2 reduction in the achievable temperature of the cooling technique. Given that in a harmonic trap the phase space density of the gas scales with temperature ( $T$ ) as  $T^{-3}$ , we expect that a factor of 2 decrease in ultimate temperature will lead to nearly an order of magnitude improvement in achievable phase space density. Again, our theory indicates that our mitigation technique is scalable, and so a reduction in induced heat beyond a factor of 2 should be possible.



Our measurements of the mitigation of reabsorption are presented in ref. [3]. In addition to being useful in CAZ cooling, this reabsorption mitigation technique is applicable to optical pumping in ultracold dense gases in general, other non-evaporative cooling methods, and efficient quantum state preparation.

## **II. Simultaneous loading of $^{85}\text{Rb}$ and $^{87}\text{Rb}$ into an optical trap from a MOT.**

While  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  have been simultaneously trapped in overlapping MOTs [4], magnetic traps [5], and optical traps loaded from a magnetic trap [6], the simultaneous loading of both of these isotopes into an optical trap from a MOT has not been reported prior to the work presented here. The simultaneous loading of these two isotopes into an optical trap is required for CAZ cooling, and loading them from a MOT is the most straightforward way to do so.

One of the most critical parameters in the predicted performance of CAZ cooling is the initial number of atoms present in the optical trap at the beginning of the cooling sequence. While the individual loading physics of both  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  had been studied previously, to what extent these isotopes might interfere with each other as they were being cooled simultaneously into the optical trap was unknown. Therefore, we studied the loading physics of these two isotopes in detail in order to begin with initial conditions that were sufficient for CAZ cooling. What we found is that these isotopes do interfere with one another during simultaneous loading. Somewhat surprisingly, this interference was not primarily through the expected channel of heteronuclear light-assisted collision-induced loss. These studies are still ongoing as part of our research program, but a preliminary characterization of our results will be given in this report.

After optimization, we were able to reliably trap up to  $2 \times 10^6$   $^{85}\text{Rb}$  and  $2 \times 10^6$   $^{87}\text{Rb}$  atoms simultaneously in the optical trap. These numbers meet the design criteria laid out in the CAZ cooling proposal, and so represent a sufficient basis from which CAZ cooling can be implemented. As part of our research into the optimum parameters for loading, we studied the role of optical molasses in efficient loading as presented in Ref. [7]. Furthermore, we expect two additional papers concerning simultaneous loading to be published from work carried out beyond the time period of this grant. The first paper details observations that we have made indicating that the presence of one of the isotopes interferes with the laser cooling efficiency of the other. The second paper describes our measurements of simultaneous loading  $^{85}\text{Rb}/^{87}\text{Rb}$  performance in

detail. Both of these papers report interisotope effects in laser cooling that are not expected from a simple picture of the cooling processes.

### **III. Characterization of heteronuclear light-assisted collisions in an optical trap**

The number of atoms loaded in an optical trap from a MOT is a function of two competing processes: atoms are cooled into the trap from the MOT via laser cooling, and this increases the number of atoms in the trap; while conversely atoms already in the trap collide inelastically in the presence of the laser cooling light and can be lost, and this reduces the number of atoms in the trap. The balance of these two processes determines the number of atoms that will be loaded into the trap. In order to understand the limitations to simultaneous isotope loading in Rb into an optical trap, we measured the light-assisted collision rates in detail both for intra- and interspecies collisions.

Such an explicit study of light-assisted collisions in a heteronuclear collection of optically trapped atoms had not been performed in Rb before this work, which we reported in Ref. [8]. The light-assisted collision rate is a function of the details of the interatomic potential between the colliding atom pair. In the heteronuclear mixture, it was possible to select potentials of very different character by selecting the state and identity of the atoms involved in the collision. Thus, it was possible to compare collision rates between long- and short-ranged potentials, purely attractive and purely repulsive potentials, and homonuclear and heteronuclear collisions.

In addition to the basic physics knowledge that was gained from these studies, the results of this work have had important practical consequences for the performance of our apparatus. Indirectly, these studies of light-assisted collisions have answered questions about the sensitivity of trap loading efficiency to small changes in cooling laser alignment. These light-assisted collision studies have also shown that while there is some interspecies light-assisted collision loss during loading, the true interference in the simultaneous loading of these isotopes does not come from heteronuclear light-assisted collisions alone.

### **Organization of the Report**

The scientific results of our studies are recorded in Refs. [3,7,8]. This report will summarize material that is available in these publically available works. In addition to the

summaries, in the sections that follow emphasis will be placed on the experimental methods and apparatus used, plus details associated with the reported measurements beyond what was included in the publications. These sections of the report are based on the three main accomplishments listed in the summary of accomplishments section above.

I also note that the senior graduate student during this project, Anthony Gorges, has begun work on this Ph. D. thesis. This thesis will be publicly available from Colorado State University and will contain even more details concerning this project. It is expected that this thesis will be published in the summer of 2009.

## **Reabsorption Mitigation**

### **Summary of published work [3]**

As has been stated above, reabsorption of scattered photons has been a major limitation to the ultimate performance of non-evaporative laser cooling techniques [2]. Reabsorption is also detrimental to the efficiency of optical pumping. The reason for this is that both laser cooling and optical pumping ultimately require scattered light to carry some physical quantity out of the gas. In the case of cooling, entropy is being removed where in the case of optical pumping the light is to carry angular momentum from the gas. If the gas is optically thick, multiple photon scatters rather than one are required in order for light to escape the gas. In that case, heat will be added to the sample as each additional photon scatter imparts a random momentum kick to the atoms in the gas. In addition, the scattered photons do not have the proper polarization to perform the cooling/pumping, and so the secondary scattering events will tend to undo the previous ones, further limiting the efficiency.

In situations where reabsorption is a problem, the most natural thing to try in order to reduce the amount of reabsorption is to detune the pumping light<sup>a</sup>. It was discovered, however, that merely detuning the laser light, even by several transition linewidths, did not remove the reabsorption significantly. The reason for this is that in addition to photon scattering events involving just one photon, two-photon Raman transitions are also possible in the gas [9]. A scattered photon and a photon from the pumping light can combine to drive a Raman transition

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<sup>a</sup> Throughout the rest of this section, I will refer to both optical pumping light and laser cooling light as the “pumping” light. In most laser cooling schemes that aim to cool to very low temperatures, optical pumping based on the atoms’ motion is used, and so this term covers both situations.



from one ground state to another that has a different momentum (see figure 1). The cross section for this process can approach the resonant scattering cross section for a one-photon scatter, and since the momentum of the atom can be changed in this process reabsorption leads to momentum diffusion and thus a heating of the gas. The two-photon Raman transition cannot be easily suppressed by detuning since both the pumping and rescattered light have the same frequency,

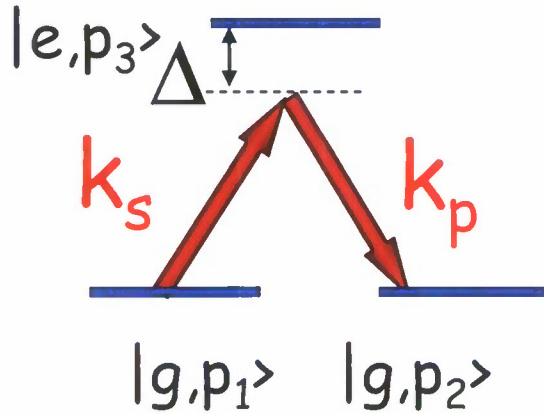


Figure 1. Two-photon spontaneous Raman transition responsible for reabsorption. One photon that resulted from spontaneous scattering ( $k_s$ ) combines with a pump photon from the laser ( $k_p$ ) to drive a transition between two ground electronic states with different momenta ( $p_1$  and  $p_2$ ). As the detuning ( $\Delta$ ) of the lasers from the excited electronic state  $|e, p_3\rangle$  is varied, the two-photon transition remains in resonance.

and thus the two-photon transition is always in resonance regardless of detuning.

Reabsorption has been mitigated by using tightly confining potentials [10], but with mixed success at very low temperatures [2]. The use of such tightly confining potentials is not easy in CAZ cooling, and so we investigated a different way of reducing the reabsorption probability. Our thinking was guided by the fact that in cases where a Raman transition is driven by two separate laser beams, care must be taken to make sure that the phase between the two beams is stable and well-defined. Thus, if the relative phase of the pumping light and the scattered light could be altered fast enough, the reabsorption probability could be reduced.

One part of inducing this phase disruption was to use two beams with

different frequencies rather than one to pump the gas. For our tests, we used beams tuned roughly 60 MHz to the blue of the  $^{85}\text{Rb}$  cycling transition with a difference frequency of 10 MHz. Merely using two beams with different frequencies is not sufficient to disrupt reabsorption in the gas, though. At the detunings used in our experiments the atomic dipoles can rapidly adjust to changes in the pumping light. Thus, while the amplitude of the pumping light varied in time, the atoms' dipoles followed the variation and the resulting scattered light maintained a good phase relationship with the pumping light.

Thus, when two co-propagating beams of different frequency were used to heat the cloud, there was no mitigation of reabsorption. When these same two beams were aligned so that they were counter-propagating, however, reabsorption mitigation was observed. The reason that the counter-propagating case is different from the co-propagating case is that in the counter-propagating case a strong spatial interference pattern was created. At any given instant in time, the light intensity in the counter-propagating case exhibits a series of bright and dark fringes separated by half a wavelength of the light. The bright and dark regions shift due to the differing frequencies of the beam, with initially dark regions becoming bright and then dark again in a period set by the beat frequency between the two beams.

In the presence of this spatial interference pattern, some atoms in the gas are in light regions and some are in dark regions, and so the amount of scattered light produced by each individual atom varies in time at the beat frequency of the two lasers. Consider the reabsorption induced in one particular atom (the "target atom") in the gas in such a case. The sources of the scattered light at the target atom's position vary in time. Since the position of the atoms in the gas is random, the phase of the light at the location of the target atom from an individual scatter is random. Thus, as the sources of the scattered light change, the phase of the scattered light observed by the target atom varies in time as well. In particular, this phase varies with respect to the phase of the pumping light, disrupting the phase-sensitive two-photon spontaneous Raman scattering that is the basis for reabsorption at these detunings.

A theory based on the optical Bloch equations was developed and used to predict the amount of reabsorption reduction observed in the counter-propagating two-beam case. It was found that a reduction of a factor of 2 was predicted, and that was consistent with the reduction observed. By extending the theory to multiple beams, it was found that the reabsorption reduction should scale with the number of beams producing a sufficient spatial interference pattern in the gas. Thus, for example, 4 beams could be used to reduce reabsorption by a factor of 4, as long as there were sufficiently large angles between the propagation directions of all 4 beams. Additional details on the reported results, including the details of the theoretical treatment, can be found in Ref. [3].

### **Experimental Apparatus**

For this set of measurements, an optical trap was not required. The cloud of ultracold atoms was produced using the now-standard technique of a Magneto-optical trap [11,12]. In



anticipation of trapping multiple isotopes of Rb, the configuration of our MOT is slightly different than what is typically used, but otherwise follows standard techniques.

In order to cool and trap a gas of ultracold atoms, a UHV environment is required. In the absence of a good vacuum, collisions with room-temperature background gas atoms remove atoms from the trap. Our vacuum was created in an all-metal stainless steel chamber (see Appendix A for a mechanical drawing of the vacuum apparatus). Standard UHV techniques such as thorough cleaning and a 300° C bakeout were used to achieve UHV conditions [13]. The chamber was designed with numerous ports for optical and electronic access. The MOT beams entered the chamber through three ports (ports A, C, H on the mechanical drawing) and then exited through the ports on the other side. On each of these exit ports a quarter-wave plate was mounted along with a mirror that retro-reflected the beams back through the chamber to create the six beams necessary for the MOT.

The light for the MOT was produced by an external cavity diode laser, following a standard design [14]. An 80 mW DL-7140-201S Sanyo laser diode was used with an 1800 lines/mm holographic grating blazed for 50% reflection in the external cavity laser. This light was then sent through an optical isolator to minimize optical feedback and then was directed towards the chamber. The laser temperature was regulated within a few mK using a thermo-electric cooler and homebuilt temperature servo electronics. The frequency of this laser was measured via a DAVLL [15] spectroscopy system. A PZT was used to control the angle of the grating in order to control the laser frequency at low bandwidth while diode laser current modulation was used to control the laser frequency at high bandwidth. Using the DAVLL signal, the laser was electronically locked to the desired frequency via a homebuilt electronic servo system that fed error signal correction to both the PZT and the laser current modulation. This setup allowed us to control the laser frequency within about 1 MHz while providing a tuning range of several hundred MHz. Desired changes in the laser frequency were achieved by simply changing the electronic set point of the laser servo system and then letting the servo system change the laser frequency in response. A saturated absorption spectroscopic set up [14] was used to calibrate the DAVLL signal to account for long-term drifts.

A block diagram of the initial optics used to shape the MOT beams is shown in figure 2. After passing through these optics, the beams were directed through quarter-wave plates set at the appropriate orientation [16] and were then sent into the chamber. Since the non-polarizing

beam-splitting cubes shown in figure 2 split the light 50/50, the axial beams were twice as strong as the individual radial beams. While this is different from the usual case for MOTs, the MOT functioned as expected and its behavior was comparable to typical MOTs despite the unusual degree of beam imbalance.

In addition to the MOT cooling light, hyperfine repump light was required as well. This light was produced by a separate external cavity diode laser. While the MOT cooling light had a wavelength of 780nm, the repump light that we used had a wavelength of 795 nm. It was produced by a Sanyo DL-8141-035A laser using the same grating and frequency stabilization

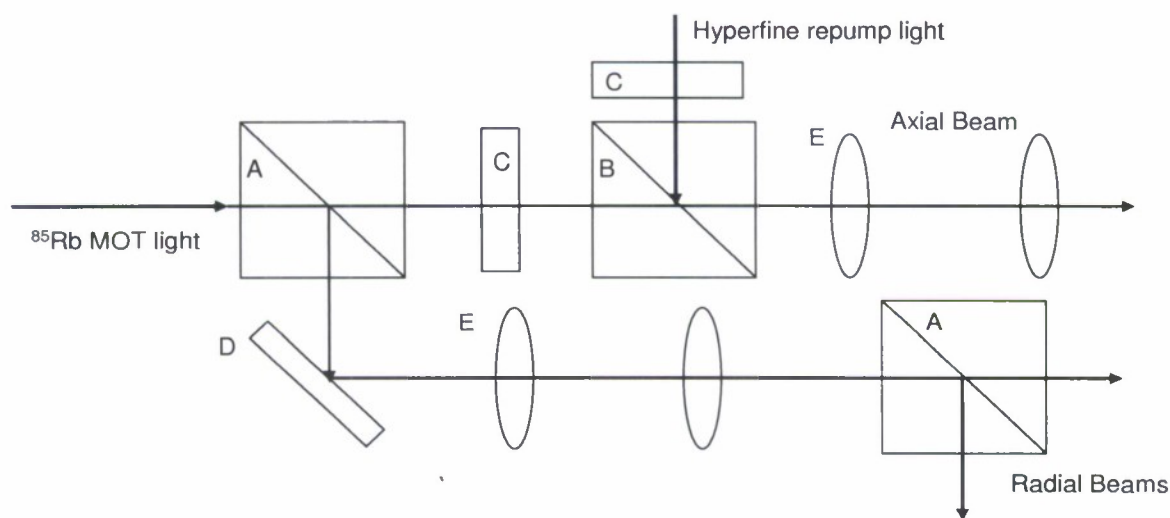


Figure 2. Block diagram of the beam shaping optics. The light from the MOT cooling external cavity diode laser ( $^{85}\text{Rb}$  MOT light) and the hyperfine repump external cavity diode laser are shown. The beams from these two lasers are split, combined, and shaped as indicated. The optics shown in the figure are: A) 50/50 nonpolarizing beamsplitting cubes, B) polarizing beam-splitting cube, C)  $\lambda/2$  wave plates, D) mirror, E) lenses to magnify the beams to the desired size.

apparatus as for the MOT cooling light. The hyperfine repump beam was directed along the direction of the axial MOT cooling light beams as shown in figure 2. Both the MOT and the hyperfine repump beam had beam diameters of about 4.00 cm. The peak intensity of a single MOT beam for the  $^{85}\text{Rb}$  cooling light was  $2.5 \text{ mW/cm}^2$  on average.

The data gathered in this reabsorption experiment consisted of time-of-flight images of the MOT atoms in order to determine the number and temperature of the atoms in the MOT. After an experimental cycle was completed, the atoms were released from the MOT for a period

of 10-20 ms. This release was accomplished by turning off all of the MOT cooling light via a shutter and the hyperfine repump light via an Acousto-optic modulator (AOM). After the 10-20ms wait period, a pulse of light from the probe laser illuminated the atoms for a period of 80  $\mu$ s. This probe laser was a separate external cavity diode laser similar in design, construction, and control to the MOT cooling light laser and the hyperfine repump laser. Our imaging was conducted on-resonance. The light pulse from the probe laser passed through a single mode fiber, then a polarizer, and then a wave plate to create a circularly polarized beam. The light was directed into the chamber via port K and exited the chamber via port Y.

Once the light exited the chamber, it was collected by a single lens which focused the image of the atoms onto a low-noise CCD camera where the image was recorded and then sent to a computer for storage and analysis. In fact, in a single measurement three images were recorded – one with the atoms present, one with the probe light present but no atoms, and one with no atoms and no probe light to measure the background. On a pixel by pixel basis, the background was subtracted from the first two images and then the resulting ratio of the background-subtracted first image to the background-subtracted second image was used to calculate the column density of the atom cloud (see Ref. [17] for details).

The resulting calculated column density was then fit to a 2D Gaussian to measure the width of the atom cloud and the number of atoms in the image. Because of the 10-20ms time of flight, the atom cloud rms velocity and therefore temperature could be measured.

### **Heating the ultracold gas with light pulses**

In order to investigate reabsorption mitigation, we induced heat in the MOT atoms via a controlled set of light pulses. These light pulses were produced by one or two additional external cavity diode lasers, as the experiment being conducted warranted (see Ref. [3]). The pulse time and duration was controlled via an AOM. In order to prevent a large center-of-mass motion from distorting our absorption measurements of the cloud, the heating pulses were directed collinearly with the probe beam path. In order to overlap the heating pulses and this path, a non-polarizing beam cube was added to the probe path before it entered the chamber and a polarizing beam cube and a quarter-wave plate were added in the probe exit beam path so that a beam could



be coupled back in the opposite direction of the probe propagation. The wave plate was adjusted so that the backward propagating light had the opposite handedness of the forward-going light<sup>b</sup>.

With the ability to send controllable pulses through the ultracold atom cloud, we could then measure the heat induced as a function of a variety of different parameters such as pulse length, pulse intensity, detuning, and co- and counter-propagating beams. A typical experimental cycle consisted of collecting about 200 million  $^{85}\text{Rb}$  atoms into the MOT. These atoms were then compressed and cooled in a CMOT stage and then a molasses stage [7]. The end result was a cloud with an on-resonant optical thickness of 10 and a temperature of 15-20  $\mu\text{K}$ . The MOT laser light was then shut off and 1 ms later the cloud was illuminated by the heating pulses. The pulse duration of these heating pulses was varied in the range of 40-1600  $\mu\text{s}$ . The hyperfine pump remained on during these heat pulses. After the heating pulses were completed, the atoms were allowed to expand freely and then a time-of-flight image was taken.

#### **Data analysis**

Once we had decided on a set of parameters, typically about 16-32 repeated images were taken under the same experimental conditions to get an average temperature and number of atoms from the data. The nature of these experiments was comparative. The heat induced under one set of conditions (e.g. with one laser on alone) was compared to the heat induced under a different set of conditions (e.g. with two simultaneous lasers). Our theory that was developed could be used to predict the resulting behavior, and our measurements confirmed the theory within their uncertainties, as described in [3] and the summary section above.

### **Simultaneous loading of $^{85}\text{Rb}$ and $^{87}\text{Rb}$ into an optical trap from a MOT**

#### **Summary of published work [7]**

As part of our CAZ design requirements, it is necessary to load at least  $2 \times 10^6$   $^{87}\text{Rb}$  and  $0.3 \times 10^6$   $^{85}\text{Rb}$  atoms into an optical trap capable of sufficient confinement. For technologically reasonable laser powers, it is not possible to load this number of atoms into an optical trap from a MOT simply by overlapping the trap, turning it on, and capturing the atoms that were already in the trap volume. Instead, atoms initially outside of the trap must be cooled into the trap via laser

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<sup>b</sup> This means that with respect to the atoms, both the forward going and backward going beams drive the same  $\Delta m$  transition, i.e. both drive the  $\Delta m = +1$  transition.

cooling to achieve these numbers. This optical trap loading involves the physics of both laser cooling and laser-induced collisional losses, as the laser cooling determines the trap loading rate and the laser-induced collisional losses determine the limiting loss rate of atoms from the trap during the loading process.

The number of atoms loaded into the trap is described by a rate equation

$$\frac{dN}{dt} = R(t) - \frac{N}{\tau} - \beta N^2 \quad (1)$$

where  $N$  is the number of atoms in the trap,  $R(t)$  is the rate at which atoms are loaded into the trap as a function of time,  $\tau$  is the one-body decay constant due to losses from things like collisions with hot background atoms in the chamber, and  $\beta$  is an effective two-body loss coefficient. For our conditions,  $\tau$  was large enough that the one-body loss term was negligible, and from here on this term is ignored. The peak number of atoms that can be trapped is therefore determined by the interplay between the load rate  $R$  and the loss rate  $\beta N^2$ .

In order to get a sufficiently high load rate  $R$ , the density of the atoms in the MOT should be made high, the temperature of the atoms in the MOT made low, and the laser cooling that occurs during the transit time of the atoms across the optical trap should damp the atoms' motion significantly. These processes are described in detail in Ref. [18]. The density and temperature of the atoms in the MOT can be manipulated by adjusting the cooling laser detuning and the hyperfine pump laser power, among other things. For our work, a typical optical trap loading cycle consisted of the following sequence: loading Rb atoms from the background vapor into the MOT for a period of about 30 seconds; dropping the hyperfine pump power and increasing the detuning of the MOT cooling laser to the red of the cycling transition to create a CMOT to increase the atom density; detuning the laser further to the red of the cycling transition and turning off the magnetic fields of the MOT to create an optical molasses; turning on the CO<sub>2</sub> trap and letting it load from the MOT atoms in the optical molasses; turning all of the trapping and repump lasers off and holding the atoms in the optical trap for a period of about 100ms to let the untrapped MOT atoms fall away; and then releasing the atoms from the optical trap and imaging them in order to determine their number and temperature. See [7,12] for details.

The effective loss coefficient  $\beta$  is determined primarily through light-assisted collisional losses. These are described in detail in the review [12]. Like the load rate  $R$ , the value of  $\beta$  is determined in part by the hyperfine pump power and the cooling laser detuning. Atoms that are



resonant with the strong cooling light are more likely to be lost from the trap due to a light-assisted collision, and so reducing the hyperfine repump power allows the atoms to spend a longer amount of time in the lower (non-resonant) hyperfine ground state, avoiding losses but also reducing the loading rate  $R$ . The detuning dependence of  $R$  and  $\beta$  acts similarly, with larger detuning producing lower loss rates but also generally lower loading rates.

To get the largest number of atoms loaded into the optical trap, the most advantageous combination of  $R$  and  $\beta$  must be selected through the choice of hyperfine pump power and cooling laser detuning. To find these parameters, we studied the optical trap loading in detail, with a particular eye towards understanding the role of an optical molasses in loading our relatively shallow optical trap [7]. Not only is Ref. [7] a report of our finding that an optical molasses is required for efficient loading, but it also details the procedure that we used to optimize the loading of Rb atoms into the optical trap. This procedure consisted of systematically altering the hyperfine pump power and optical molasses stage detuning and duration to find the set of conditions which resulted in the largest number of atoms in the optical trap for a given alignment of the cooling and hyperfine pump lasers.

In the course of our studies, we found that the values of  $R$  and  $\beta$  would vary for what should have been the same set of experimental parameters. These parameters tended to vary together, meaning that the number of atoms trapped was more stable than  $R$  and  $\beta$  individually. We found through explicit measurement that small changes in alignment could produce large changes in both  $R$  and, more surprisingly,  $\beta$ . These measurements will be described in more detail in a subsection below.

As mentioned in the text above, we found that an optical molasses stage was critical for getting the largest number of atoms loaded into the optical trap. The difference between the optical molasses and the MOT is just the presence of a magnetic field produced by a pair of anti-Helmholtz coils. This field is necessary to confine the atoms in the MOT, but it inhibits the lowest achievable temperatures for the ultracold atom cloud. We found that it inhibited the loading efficiency into the optical trap, too. This resulted in a lower rate for  $R$  for loading without a molasses stage than with the molasses stage for parameters that produced the same value of  $\beta$ . The improvement gained by having a molasses stage was a factor of 2 greater atom number loaded than without this stage.

By adding a deliberately induced magnetic field during molasses stage loading, we were able to show that fields on the order of those found from the anti-Helmholtz coils were large enough to inhibit the optical trap loading. In the presence of a magnetic field, optical molasses does not cool the atoms towards zero velocity, but rather towards a finite velocity greater than zero. This means that the velocity damping rate due to laser cooling an atom experiences at a particular velocity is generally less in the presence of a magnetic field than without one present. This decrease in damping rate was enough that some of the atoms that would have been slowed enough to be trapped as they crossed the optical trap volume were no longer slowed sufficiently in the presence of a magnetic field.

### **Experimental Apparatus**

The vacuum chamber and absorption imaging system were the same in this set of measurements as described in the Experimental Apparatus section of the reabsorption mitigation section above. The MOT cooling lasers and hyperfine repump laser for  $^{85}\text{Rb}$  were also the same as above. Changes to the apparatus between the reabsorption and optical trap loading measurements were made, though. The changes to the apparatus consisted of the addition of the optical trap and the added capability to simultaneously trap  $^{87}\text{Rb}$  and  $^{85}\text{Rb}$  in MOTs in the same region of space simultaneously. These changes along with some implications of our results not contained in the published works are presented in the remainder of this section.

### **The optical trap laser**

Once we had completed our reabsorption studies, we proceeded with optically trapping  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  alone, and then the two isotopes simultaneously. This required the installation of the optical trapping laser. To perform the optical trapping we use a 50W Coherent Gem-Select 50 scientific grade  $\text{CO}_2$  laser operating at  $10.6\text{ }\mu\text{m}$ . This laser beam is directed into an AOM to control the light intensity. Our coupling is such that about 33 W of light are available after the AOM. The deflected beam of the AOM is directed to a set of three ZnSe lenses that are used to preliminarily shape the beam to a desired spot size. The  $\text{CO}_2$  laser beam then passes through a periscope that directs the beam into the chamber. After the periscope, there are two more ZnSe lenses. The first is mounted on an XYZ translation stage and forms a focused spot at a point in space outside the vacuum chamber. This spot is then imaged onto the atoms via a lens performing 1:1 imaging. This allows us to have flexibility in the type of focusing that can be done while still allowing the ability to achieve a small spot size at the location of the atoms. In

the end, 28W of power is delivered to the atoms with a spot size of about 100  $\mu\text{m}$ . After passing through the center of the chamber, the  $\text{CO}_2$  beam exits the chamber through another ZnSe window where it is directed into a beam dump, which was constructed using an anodized aluminum tube bent at a 90 degree angle.

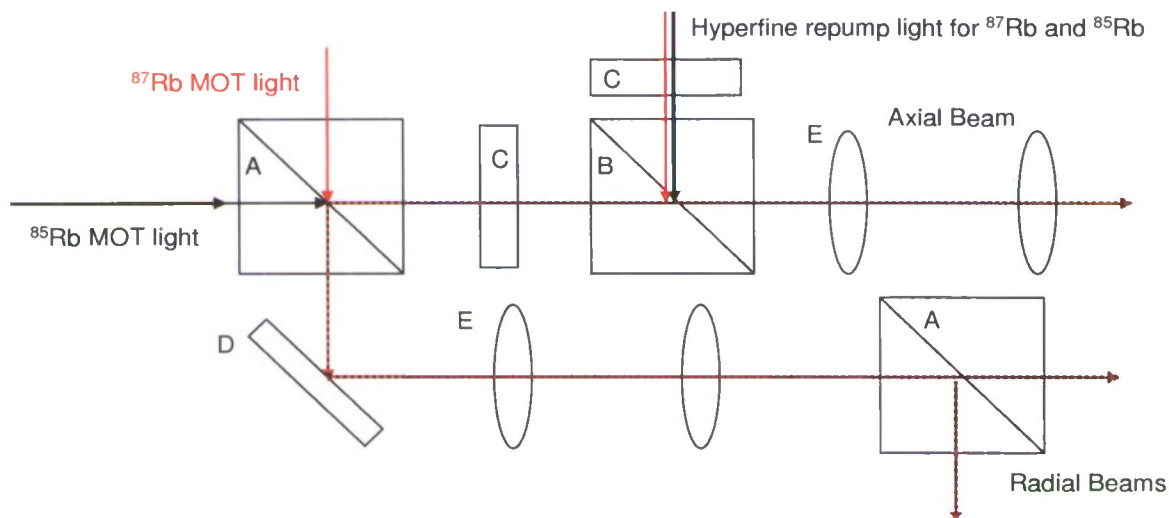


Figure 3. Same as figure 2, but showing the  $^{87}\text{Rb}$  MOT cooling light and  $^{87}\text{Rb}$  hyperfine repump light paths. The hyperfine repumps were overlapped using a 50/50 beamsplitter before entering this part of the beam path. In this part of the diagram, they are showed as offset for clarity.

### Dual trapping – apparatus modifications

In order to simultaneously trap both  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  in the optical trap, one basic requirement is that these two isotopes be trapped simultaneously in MOTs that are located in the same region of space. We accomplished this by using a 50/50 beamsplitter to overlap both the MOT laser cooling beams with one another and another 50/50 beamsplitter to overlap the hyperfine repump beams with one another. Once this had been done, the combined beams passed through the relevant optics and were shaped and polarized as required for the MOTs. See figure 3 for details.

The main drawback with this design is that the axial beam of the MOT had roughly twice the power of the radial beams. We experimented with a more balanced beam distribution by attenuating the axial beam, but the loss in power caused a loss of atoms trapped in the MOT and



also reduced the loading rate into the optical trap. Thus, having the additional power seems to be more beneficial than balancing the powers contained in the beams.

### **Overlapping the CO<sub>2</sub> beam with the ultracold atom cloud**

There is a technical challenge in overlapping the focus of the CO<sub>2</sub> laser beam with the location of the ultracold atom cloud of the MOT. The volume of the MOT is about 1 mm<sup>3</sup> while the spot size of the CO<sub>2</sub> laser is about (0.1 mm)<sup>2</sup> and the Rayleigh length along the beam propagation direction is about 3mm, giving a characteristic volume of the CO<sub>2</sub> trapping region of about 0.06 mm<sup>3</sup>. The center of the atom cloud is located at a distance of about 10 cm from the outside of the chamber, and so the alignment is nontrivial.

We found that our ability to use the 1:1 imaging lens made the following technique successful. We trapped <sup>85</sup>Rb atoms in the MOT and then used the ZnSe lens in the chamber to image the fluorescence of the MOT atoms onto a small CCD array. By moving around the CCD array, the image could be brought into focus and centered. We were then able to determine the location outside the chamber that would be imaged onto the atoms inside the chamber. We placed a metal aperture centered on this location in space and then directed the CO<sub>2</sub> beam through it. We adjusted the position of the lens on the XYZ translation stage so that the focus of the CO<sub>2</sub> was slightly offset from the location of the aperture in the beam propagation direction. It is hard to be precise about this offset because the location of the focus was hard to measure<sup>c</sup>. We then took a series of images of the MOT atoms while translating the XYZ mounted lens in the XY directions (i.e. those perpendicular to the direction of the beam travel). Since the focus of the CO<sub>2</sub> beam was not overlapped at the plane of the atoms, the beam was both much larger than at its focus and diverging. When overlapped with the atoms, the attractive potential created by the CO<sub>2</sub> beam would then tug them slightly in one direction. Once this was observed, the alignment of the CO<sub>2</sub> beam could be adjusted by monitoring its effect on the atoms until it was well overlapped. Once overlapped, the system has been stable for periods on the order of a year.

### **Optimization of the number of atoms trapped in the optical trap – single isotope trapping**

Once the optical trap was overlapped with the atoms, we proceeded to load as many into the trap as possible. Guided by [18], we adjusted the hyperfine pump power and the MOT cooling laser detuning during the loading stage to load as many atoms as possible. Early in this

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<sup>c</sup> We determined the location and size of the CO<sub>2</sub> beam by burning holes in Tyvek paper. The Tyvek was useful since it burns in a relatively smoke-free manner. To find the focus using this technique, we turned the power of the CO<sub>2</sub> beam down as far as we could so that only at the focus would we quickly burn a small spot.

optimization process, however, it became clear that the precise alignment of the six MOT cooling laser beams, and to a lesser extent the hyperfine repump beam alignment, played an important role in the optimization of the number of atoms loaded into the optical trap. At first, we adjusted the individual beam alignments while monitoring the number of atoms trapped in the optical trap to search for a maximum. While doing this, we found that improving the quality of the optical molasses was linked to improving the loading into the optical trap. The quality of the optical molasses was determined by watching the atoms in the MOT expand after the anti-Helmholtz field was deliberately shut off. If the resulting expansion of the atom cloud was slow and even, that was a “good” molasses. If the atoms moved predominantly in one direction and moved away quickly, that was a “bad” molasses. By adjusting the beam alignment and shimmming out stray magnetic fields so that we had a “good” optical molasses instead of a “bad” one, we were quickly able to improve the number of atoms trapped in the optical trap. Subsequent optimization of the alignment from that point improved the number of trapped atoms even more, but it was still the case that the optimum of the loading was found at a position of “good” optical molasses.

Eventually, we were able to trap over  $5 \times 10^6$   $^{85}\text{Rb}$  atoms and  $3.5 \times 10^6$   $^{87}\text{Rb}$  atoms into the optical trap individually. These numbers were not achieved with the same external cavity diode laser, however. In the course of our studies, we found that greater cooling laser intensity was required to trap  $^{87}\text{Rb}$  than  $^{85}\text{Rb}$ . Partly, we believe that this stems from the fact that since the natural abundance of  $^{87}\text{Rb}$  is lower (28%) than for  $^{85}\text{Rb}$  (72%), greater laser power was needed to trap the same number of atoms in the MOT during the MOT loading stage. In addition, the light-assisted collision loss rates are not the same for  $^{85}\text{Rb}$  as for  $^{87}\text{Rb}$ , even when the same laser power is used [8]. The relatively higher loss rates for  $^{87}\text{Rb}$  may necessitate relatively higher load rates  $R$  and thus relatively higher laser intensities for roughly the same performance.

Because of this requirement of higher laser intensity for the  $^{87}\text{Rb}$  atoms, we did not use a simple external cavity diode laser for the  $^{87}\text{Rb}$  trapping light. Instead, we use an external cavity diode laser to injection lock a relatively high power (120 mW) Sharp GH0781JA2C. This roughly doubled the power that is available for trapping and resulted in a significant improvement in performance. As a check, we occasionally used the external cavity diode laser that normally provides the  $^{85}\text{Rb}$  trapping light to trap  $^{87}\text{Rb}$  instead. Even though this laser was capable of loading  $5 \times 10^6$   $^{85}\text{Rb}$  atoms into the optical trap, for  $^{87}\text{Rb}$  it typically loads under one



million atoms. While the alignment of the laser was not changed during this check and so may not be optimal for  $^{87}\text{Rb}$ , this shows the sensitivity to trapping power that  $^{87}\text{Rb}$  possesses.

### **Experimental Apparatus Stability**

In the course of our investigations, we observed substantial (up to 30%) drifts in the measured values of  $R$  and  $\beta$  for both  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  over both daily and weekly periods. We were able to correlate the daily variations to temperature drifts in the laboratory and by adding additional cooling capacity to reduce these variations we were able to substantially reduce the associated daily drifts. The longer-term drifts, however, remained. Measurements indicated that the drifts were not due to changes in laser detuning, laser power, magnetic field drifts, or changes in the power balance between the radial and axial beams. The remaining likely candidates were drifts in laser alignment and possibly drift in laser polarization.

In order to investigate the possibility that alignment variations were the culprit, we deliberately changed the alignment of one of the retro-reflected laser beams in one of the radial directions of the MOT. By making a change of about 10 milliradians, we were able to radically alter the value of the two-body loss coefficient,  $\beta$ , during the trap loading process, increasing it by a factor of 2. Previous measurements had indicated that through changing the alignment of the beams the value of  $R$  could be affected, and so it appears that both  $R$  and  $\beta$  were functions of beam alignment.

Initially, the variation of  $\beta$  came as a surprise. Calculations of the polarization interference pattern that resulted from the overlap of the six MOT beams, however, showed that the 10 milliradian alteration of beam we deliberately misaligned would produce significant shifts in the polarization pattern of the cooling light. It thus seems likely that a change in alignment can result in a change in the average spin state distribution of the atoms in the light field. Our observations of the light-assisted collision rate [8 and following section] were consistent with the value of  $\beta$  being dependent on the spin state of the atoms involved in the collision, explaining the dependence of  $\beta$  on alignment.

While 10 milliradians of misalignment is not a reasonable variation with time for this particular beam path alone, there are some long lever arms that were present in the system where a much smaller angle displacement would produce a comparable change in the resulting polarization interference pattern of the beams in the MOT. In addition, birefringence drifts were possible in some of the optics in the system.

Fortunately, the values of  $R$  and  $\beta$  tended to drift together. So, while the individual parameters varied significantly, the number of atoms trapped in the optical trap did not vary as much. In any case, we are introducing improvements in the apparatus to try to reduce these variations and improve the long-term stability of the apparatus.

#### **Notes on dual isotope loading**

At first, when we trapped both  $^{87}\text{Rb}$  and  $^{85}\text{Rb}$  in the optical trap simultaneously, the performance of the loading was somewhat baffling. The individual atomic transitions needed for repumping and cooling these different isotopes are separated from one another by hundreds of natural linewidths. Thus, we did not expect that the trapping and repump light for one isotope would affect the other isotope. Indeed, subsequent measurements have shown that when loading one isotope the presence of the other isotope's laser light alone did not alter the loading and loss rates significantly. With respect to interisotope light-assisted collisions, in general heteronuclear collisions are shorter-ranged than homonuclear ones. Since on average there were less pairs of atoms in the gas with small separations than large ones, the light-assisted collisions were expected to be less for interisotope collisions as compared to intraisotope collisions. Subsequent measurements (see the next section) showed this to be the case. Overall, then, we expected that the presence of one isotope would likely have had little effect on the other when loading the optical trap.

This was not observed to be the case. Generally, the sum of the number of the two isotopes that could be trapped did not significantly exceed the maximum number of atoms of a single isotope that could be trapped. Far from acting independently from one another, the two isotopes instead acted more like they were not separate isotopes. Models of the loading process that included only the measured single-isotope loading rates  $R$  (i.e. the value of  $R$  obtained when the other isotope was not present) and the measured homo- and heteronuclear values of  $\beta$  consistently failed to reproduce the observed behavior of the optical trap loading with both isotopes present.

Subsequent measurements completed after the end of this grant period indicated that despite the large difference in atomic resonance frequencies, the presence of a second isotope interferes with the laser cooling efficiency of the first. The most consistent picture that emerges from our data is that long-range spin-dependent collisions occur in which the induced dipole moments of the two separate isotopes can interact. As a result of the spin-dependent nature of

these collisions, decoherence is introduced between ground magnetic sublevels states. This decoherence interferes with the ground state coherences created by the polarization gradients in the light field. Since these coherences contribute to effective laser cooling and have an impact on the rate of pumping between the different hyperfine states, disrupting them reduces cooling efficiency and results in measurably lower values of  $R$ .

While this physics is not favorable to the specific goals of this project, it is interesting nonetheless. These decohering collisions would impact situations in which collisions occur between any two different isotopes in light fields that induce dipole moments in them. We expect to report aspects of this interference in two separate publications in 2009. For the purposes of CAZ cooling, the good news is that while the two isotope loading did not proceed precisely as expected, we were still able to simultaneously load enough atoms into the optical trap to meet the design goals of the project.

## **Light-assisted collisions in a heteronuclear gas confined in an optical trap**

### **Summary of published work**

In order to understand the optical trap loading performance in detail, it is necessary to know homo- and heteronuclear light-assisted collisional loss rates. Thus, as part of our studies in optical trap loading, we measured numerous light-assisted collision loss rates explicitly. There were additional reasons to do so. First, by using two different isotopes there was a range of different interatomic potentials that can be selected as relevant to the collisions that occurred. By systematically varying the states and identities of the atoms involved in the collision, it was possible to look at the influence of different properties of the interatomic potentials on the light-assisted collision rates. The most obvious properties we could vary were the range of the potentials and their attractive vs. repulsive character. Second, since the two isotopes of Rb have nearly the same mass and the same resonant frequencies, any variation in the light-assisted collision rate would be due to the variation in the nature of the potential alone, allowing a clean comparison of different interatomic potentials. Finally, since the optical trap was very shallow compared to a MOT, any light-assisted collision that resulted in almost any net acceleration caused the atom pair to be lost, simplifying the interpretation of the measured loss rates.



Our measurements have been reported in Ref. [8]. We were able to elucidate several general trends in the light-assisted collision rates:

1. Longer-ranged potentials have greater loss rates than short-ranged ones. This is consistent with the fact that there are more pairs of atoms with larger separations than smaller ones.
2. Potentials with a predominantly repulsive character are less lossy than ones with a predominantly attractive character. While this appears to make intuitive sense at first glance, the result was in fact somewhat surprising. At the relevant interatomic separations where the light-assisted loss is expected to occur, an excitation of the atom pair from the ground state to the excited state will result in enough acceleration during an atomic lifetime for the pair to escape from the trap in both the attractive and the repulsive potential case. Thus, it is not initially clear that there would be a substantial difference between attractive and repulsive potentials.
3. The homonuclear light-assisted collision rates were saturated at our laser intensities for our experimental conditions. While both the  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  rates were saturated, they saturated at different collision rates.
4. The homonuclear loss rates were consistently greater than the heteronuclear loss rates.
5. Simple models that did not account for the complicated interatomic potential structure arising from the hyperfine structure of the Rb atoms did not quantitatively reproduce our observed data.

In addition to these general trends, we were able to measure the light-assisted collision rate coefficients themselves to an estimated accuracy of 40%.

Our conclusion in Ref. [8] that the detailed structure of the excited state potentials plays a role in the resulting collision rate is consistent with the subsequent observations that we have made concerning the dependence of  $\beta$  on the alignment of the MOT laser beams. The knowledge of the trends and magnitude of the light-assisted collision losses was instrumental in the discovery of the true limitations to the dual isotope loading efficiency.

### **Experimental Apparatus**

The configuration of the experimental apparatus for this measurement matched that of the dual isotope loading described in the previous section. Data were collected by loading one or



more of the isotopes of Rb into the optical trap, applying a brief laser pulse, and then measuring the resulting losses. All of this could be done using the apparatus layout described above.

### **Adaptations of our imaging techniques to measuring light-assisted collision losses**

The most challenging systematic that we had to deal with in this measurement is the fact that, for certain combinations of laser light pulses and atom states, the light pulses could induce heat as well as light-assisted collision loss. In more typical laser cooling situations, atom densities as high as those in our optical trap are achieved via a significant reduction in hyperfine repump power. This causes the atoms to spend more time in the lower hyperfine state where they do not scatter the laser cooling light, since that leads to repulsive interatomic forces and heating due to incoherent scattering between the atoms [19]. In order to perform our measurements, however, it was necessary that all of the atoms occasionally be in the upper hyperfine state. In that case, because of the high density, the applied light pulses induced heat as well as loss.

By itself, heat would not cause any difficulty with the measurement of the light-assisted collision losses. However, heating the cloud produced loss via evaporation over a timescale of tens of milliseconds, and it is possible to confuse this evaporative-cooling induced loss with light-assisted collision loss. Typically, after the light pulse was applied and light-assisted collisions occurred, some of the atoms that escape from the trap due to these light-assisted collisions did so with velocities on the order of several cm/s. Since these atoms were not trapped, they fell away from the trapping region due to gravity. It took about 50 milliseconds for the atoms to fall away from the imaging region, and so in that time the heat-induced evaporative loss contaminated the measurement of the light-assisted collision loss.

Our solution to this problem was to image the atoms within 5 ms of the light pulse used to induce the losses. This had the disadvantage that some of the untrapped atoms lost from the optical trap are still in the imaging region. However, these atoms were not in the precise region of space where the optical trap was located. Thus, we took two sets of images per measurement. In the first, we left the optical trap on. Any trapped atoms were thus confined to a region of space about 40  $\mu\text{m}$  wide. This region was excluded from the processed image of the atoms, giving a count of the untrapped atoms. The experimental conditions were set to be the same, and then a second image was taken in a repeated experimental cycle. In this case, the atoms were released from the optical trap. These total atoms in the imaging region were counted in this

second case. By subtracting the number of untrapped atoms measured in the previous image, the number of trapped atoms could be determined.

In the absence of this procedure, we were not measuring only light-induced collision losses when we measured the number of atoms lost after the light pulse. This produced systematic errors such that the observed density dependence of the measured loss did not match expectations for a two-body collision. Introducing the subtraction method for the imaging analysis removed this and other discrepancies. We have explicitly verified that the trap loading loss rates have a two-body character by making a detailed measurement of the loss as a function of light-pulse time.

As an aside, we note that for measurements of two-body collision rates during trap loading, these heating issues were not a concern since the hyperfine pump power remained low in those cases.

### **Volume determination**

While the number of atoms could be measured using our imaging techniques, in order to extract a light-assisted collision rate the density of atoms in the trap needed to be known as well. This required a measurement of the volume of the atoms in the optical trap.

Since the optical trap is formed by focusing the CO<sub>2</sub> laser beam to a spot, it has cylindrical symmetry. The trap is not spherical, however. It has a large aspect ratio, being cigar-shaped with a ratio of 45 between the axial and radial trapping frequencies. The spatial extent of an ultracold cloud of atoms in equilibrium in the trap is much longer in the axial direction than in the radial. For atom clouds at 15  $\mu$ K, the axial extent (rms size of 0.8 mm) is long enough that it can be measured directly. The rms size of the radial direction, however, is smaller than the resolution limit of our imaging system. Therefore, the radial size of the cloud cannot be measured directly.

Instead, we measured the atoms' oscillation frequency in the radial direction of the trap, and then combined this with a measurement of the atoms' temperature to determine the rms size of the atoms in the optical trap. The temperature of the atoms was determined via time-of-flight expansion. To image the atoms in the optical trap, the trap was first turned off rapidly. The atoms then expand ballistically for 5 ms. In this time, the radial extent of the atom cloud was determined almost entirely by the rms velocity of the atoms since its size was much greater than its spatial extent in the trap, and so its rms velocity can be measured.

The trap oscillation frequency was measured by using parametric heating [20]. This was accomplished by varying the intensity of the CO<sub>2</sub> laser beam sinusoidally. When the frequency of this intensity variation is equal to twice the trap frequency, the cloud is parametrically heated. This was detected by an increase in the width of the cloud in the time-of-flight image, and the frequency that induced maximum parametric heating is equal to twice the radial trapping frequency. Combining this information with the rms radial velocity distribution allowed us to calculate the radial spatial extent of the atoms while they were in the trap.

### **Implications for CAZ cooling**

If light-assisted collisions occur during the optical pumping cycle of CAZ cooling they would, of course, be detrimental to the cooling efficiency since they would result in loss and possibly heating in the gas. Fortunately, in CAZ cooling the required light intensities will be  $10^3$ - $10^4$  times lower than in the studies we have recently completed. While we observed saturation in the homonuclear light-assisted collision rates, we did not observe them in the heteronuclear rates and this suggests that the loss rates will scale with the light intensity, and thus will be much lower for CAZ cooling.

In addition, the knowledge of the trends in the loss rates will be useful in choosing appropriate transitions to minimize any impact of light-assisted collision losses during the cooling sequence. There are several ways that the optical pumping in CAZ cooling can be configured, each of them with advantages and disadvantages with respect to pumping efficiency and reabsorption probability. Each configuration will also have its own associated light-assisted collision loss rate as well. There are some configurations that involve states with purely repulsive interatomic potentials, and some with purely attractive or mixed repulsive and attractive interatomic potentials. If we determine that light-assisted collisions are a detectable problem in CAZ cooling, our measurements in [8] indicate that by using the configurations that have purely repulsive potentials we should minimize the associated light-assisted collision loss rates.

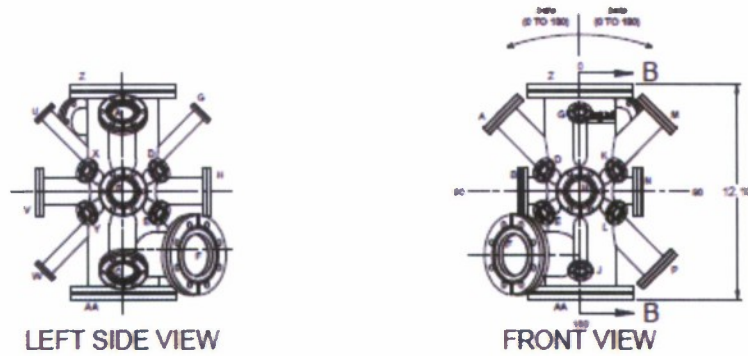
### **Closing Summary**

In the course of our research we have answered questions about and explored solutions to critical issues regarding the successful implementation of CAZ cooling. We have been the first to report the simultaneous loading of <sup>85</sup>Rb and <sup>87</sup>Rb from a MOT into an optical trap. The physics of this loading has been investigated and used to optimize the number of atoms in the

optical trap. These investigations resulted in achieving more than the design goal for the number of initially trapped atoms required for CAZ cooling. We have measured light-assisted collision loss rates in the optical trap for both hetero- and homonuclear collisions using a variety of states. From these measurements, we were able to elucidate general trends in the behavior of the collision rates as a function of the properties of the relevant interatomic potential involved in the collision. From our determination of the values of the collision rates, we learned that the decrease in the maximum number of  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  that can be trapped simultaneously as opposed to individually is not due to interspecies light-assisted collisions, as we would have initially expected. Instead, we found that the presence of one isotope interferes with the laser cooling efficiency of the other. Details of the physics of this interference were studied after the conclusion of the grant period and will be reported in future publications in 2009.



## Appendix A



Mechanical drawing of the vacuum chamber. All dimensions are specified in inches.

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